SUPERCONDUCTING NB FILM FOR RF APPLICATIONS

A. Cianchi#, L. Catani, R. Russo, S.Tazzari, Università di Roma "Tor Vergata" and INFN-RM2, 00133 Roma (Italy)
A. Andreone, G. Cifariello, E. Di Gennaro,G. Lamura, Università di Napoli "Federico II" and INFM-Napoli, 80125 Napoli (Italy)
J.Lagner, Andrzej Soltan Institute 05-400 Otwock/Swierk (Poland)
Y.Akhmadeev, Institute of High Current Electronics, 634055 Tomks (Russia)

Abstract

Copper RF cavities coated with thin Nb (Nb) films are an interesting possible alternative to bulk-Nb ones because copper is cheaper than Nb, has higher thermal conductivity and better mechanical properties. Unfortunately, the observed degradation of the quality factor (Q) with increasing electric field shown by Nb-sputtered cavities makes them unsuitable for future very high energy linear accelerators needing gradients higher than ≈15MV/m. We are therefore developing an alternate deposition technology, based on a cathodic arc system working in UHV conditions. Its main advantages compared to standard sputtering are the ionized state of the evaporated material, the absence of gases to sustain the discharge, the much higher energy of atoms reaching the substrate surface and, possibly, higher deposition rates. To ignite the arc we use a Nd-YAG pulsed laser focused on the cathode surface which proves a reliable and ultraclean trigger. Recent results on the characterization of Nb film samples produced under different conditions are presented proving that the technique can in principle produce bulk-like films suitable for RF superconducting applications.

INTRODUCTION

High field super conducting (SC) cavities for particle acceleration are at present based on Nb bulk technology although Nb coated Cu offers several advantages such as better mechanical stability, lower cost, better thermal stability, easier conditioning on the machine, easier connection to the cryostat, less sensitivity to magnetic fields, as shown by their very successful operation of the LEP II, acceleration system. So far though, the quality factor of magnetron sputtered cavities slopes down with increasing electric field [1], thereby preventing them from being used for the new very high-energy, high field SC linear accelerators. The reason for the Q slope is not yet well understood but could well be connected with the film quality. We therefore started exploring alternative coating method, cathodic arc deposition,

Vacuum arc deposition is known to be a powerful technique to produce films on several materials [2]. Its main advantages, compared to the standard sputtering process, are the highly ionized state of the evaporated material, the absence of gases to sustain the discharge and the high energy (about 50eV) of atoms reaching the substrate surface, which translate with higher film density, better adhesion to the substrate, and possibly more favourable film morphology. The technique is thus a candidate for replacing magnetron sputtering in trying to produce films having bulk–like properties but, to obtain very pure films we had to develop it so as to be able to operate the arc in in ultra high vacuum (UHV).

The main disadvantage of the arc technique is the production of microdroplets (or macroparticles) with typical dimensions in the range from 0.1 to 10μm, emitted from the region of the arc spot and consisting of molten cathode material. Microdroplets become charged with electrons during their passage trough the plasma region near the cathode and accelerated to high energy. They solidify during their flight to the anode and can become embedded in the growing film. While not contaminating the film, the droplets may create voids, increase the surface roughness and become possible sources of field emission. They should therefore be filtered out.

EXPERIMENTAL SETUP

Results presented here have been obtained with both unfiltered and filtered (to decrease the number of microdroplets) UHV planar arc set-ups. In both cases, the planar arc source is housed in a UHV chamber pumped down to 10^{-10} Torr by an oil-free pumping system consisting of a membrane pump on the fore line of a drag turbo molecular pump. The conical cathode is fabricated from a 50mm diameter high purity Nb rod fastened to a water-cooled Cu support. An interposed Ga-In eutectic mixture ensures a good thermal contact between Nb and Cu. The vacuum chamber around the Nb cathode is also conical, fabricated from a single stainless steel rod, with a final inner diameter of 90mm. More details are found in ref.[3].

To ignite the arc one must produce a small plasma burst of a sufficient density to form a high-conductivity path between cathode and anode. Eventually the best method to produce the initial plasma burst was found to be laser ablation of the cathode material by focusing an external laser beam, through a quartz window, onto the cathode itself; a pneumatic shutter prevents coating of the window when the arc discharge is running. The method is absolutely clean and proved more reliable than any other solution tried.

#cianchi@roma2.infn.it

Several substrate samples are fastened to a sample holder massive flange placed at a distance of about 50cm from the cathode; a rotating shutter allows coating one sample a time. The sample holder is electrical insulated from the grounded vacuum chamber, so that a bias can be applied to samples in order to reflect electrons and avoid uncontrolled, excessive sample heating. The bias is also beneficial in that it further accelerates the ions. Figure 1a) shows a picture of the system.

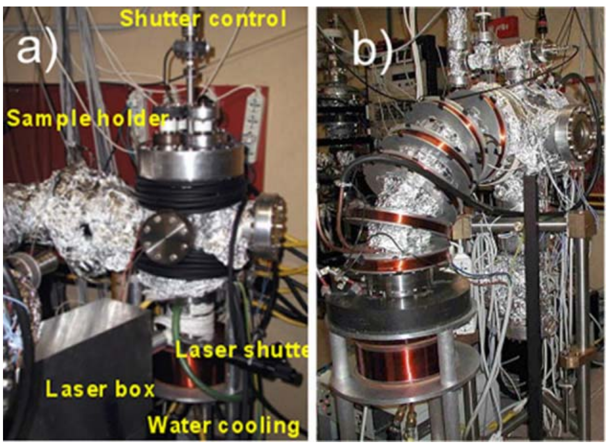

Fig. 1: Layout of the planar arc systems: unfiltered (a) and filtered (b)

To reduce the number of microdroplets reaching the sample a magnetic filter has been studied and built. A number of coils surrounding an elbow shaped chamber force electrons to spiral along the magnetic field lines with orbit radii smaller than the vacuum chamber elbow one. Since the plasma is quasi-neutral the ions follow the electrons through the elbow, while massive macroparticles hit the chamber walls and are stopped.
Samples are mounted on a sample holder placed 30cm downstream from the 90° elbow.
Fig. 1b) shows a picture of the system and Fig.2 the effect of the filter on the number of microdroplets on film.

Fig. 2: Comparison between samples deposited with the unfiltered (left) and filtered (right) planar arc system. Image sizes are 252X189μm

DC AND MORPHOLOGICAL FILM PROPERTIES

Samples have been obtained with RRR ranging from 10 to 80 even for film thicknesses of a few thousand Å only, with excellent reproducibility. Such RRR values are more than twice those usually obtained under similar conditions (same thickness and coating temperature) by magnetron sputtering (RRR usually between 5 and 10). Critical current density (J_c) and superconducting critical temperature (T_c) of the film are measured using an inductive method consisting in passing a 1 KHz alternate current through a coil placed on the sample surface. The coil serves both as exciter and as pick-up: a lock-in amplifier in fact records the third harmonic signal generated during the transition between the normal and the superconducting phase. Typical results, in good agreement with Nb bulk (T_c= 9.26K, ΔT_c ~0.01K) data, are shown in Fig.4.

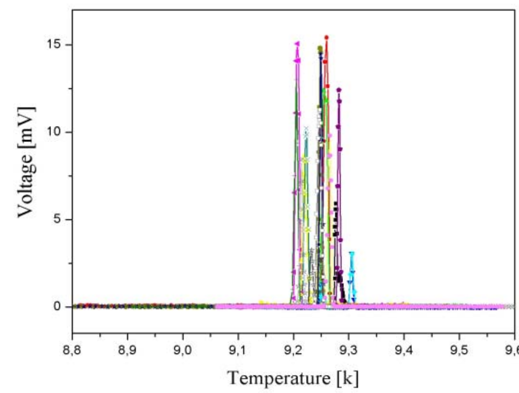

Fig. 3: Transition curve of several Nb films deposited on copper and sapphire. T_c is 9.25K within 0.05K and transition widths are smaller than 0.02K.

The critical temperature T_C is here defined as the temperature at which the transition starts, while the transition width is defined as the temperature variation to complete the transition. In our samples the width is very narrow (0.01 – 0.02K), a strong indication that the films are very homogeneous.

The Nb film structure has been analysed using X-ray diffraction and atomic force microscopy. X-ray diffraction spectra (see [4]) are collected using Cu–κ radiation with filtered K_β line, in the θ–2θ configuration. The results range from 0.3306 to 0.3318nm, indicating a much lower stress than observed in Nb deposited by magnetron sputtering on copper substrates [4], a result in agreement with T_C measurements. Also the width of the diffraction peak is slightly narrower than in the sputtering case, an indication of larger and/or more ordered grains. This result is confirmed by Atomic Force Microscope pictures showing an average Nb grain size of 200nm. The roughness of Nb samples deposited on copper is comparable to that of the copper substrate itself while that of films on sapphire is much smaller. This clearly indicates that, on copper, film roughness is determined by the substrate. When using a magnetic filter against microdroplets the roughness of arc deposited Nb samples on sapphire is observed to be of the order of few tenth of a nm, comparable to that of Nb sputtered films deposited on the same substrate.
Nb-coated surface on copper and sapphire substrates were also examined by SEM (Philips 515). Growth of

columnar structures is observed in the picture of Figure 4a): the columnar structure is visible on the wall of a deep crater left by an early, large droplet. Looking with higher magnification inside the crater, Germ-formation of crystallites Nb is observed, germs having typical size of ~50-100nm (Fig.4b) and are densely enough packed to form a uniform film on surface as shown in Fig. 4a).

Growth of columnar structures growing all the way through the ~1.5μm thick film and with a typical diameter of ~100nm are seen to develop from the early germs as the film grows in Fig.4b).

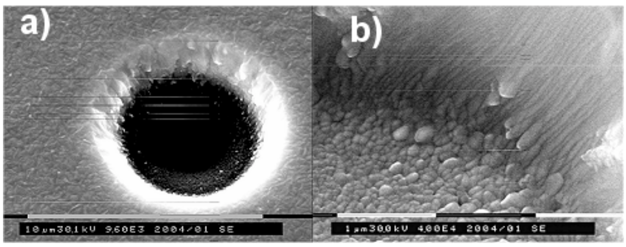

Fig. 4: a) Columnar crystallites as high as the 1,5μm film are visible on the wall of a deep crater. b) Germs of crystallites at the bottom of a crater left after removal of a droplet from a copper substrate sample

LOW FIELD RF PROPERTIES

Measurements of the surface impedance Z_s (T, H) as a function of temperature were carried out by a dielectric resonant cavity technique. The high purity (RRR > 500), 20GHz Nb resonator is a D = 9.5mm diameter cylindrical cavity short-circuited at both ends by plates which can be replaced by the samples to be measured. A cylindrical dielectric sapphire rod with diameter d = 7mm and height h = 3.5mm is placed and centered between the two parallel plates (see Fig. 5). The TE_{011} mode of the resonator is excited and detected by two semi-rigid coaxial cables each having a small loop at the end; the resonant frequency f and Q-factor are measured in the transmission configuration.

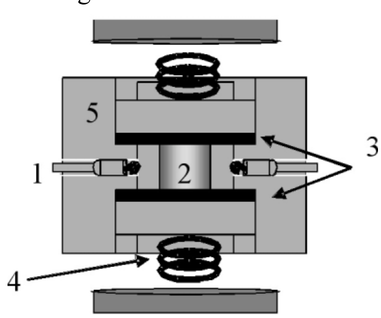

Figure 5: schematic drawing (not to scale) of the 20GHz dielectrically loaded resonator: coupling ports (1), sapphire puck (2), superconducting sample(s) under test (3), Cu-Be springs (4), cavity walls (5). The effective surface resistance R_s of two Nb bulk samples, having nominally the same structural, transport and superconducting properties as the lateral walls, is first obtained measuring the (unloaded) quality factor Q_{un} of the resonator. The measurement is then repeated replacing the bulk Nb end plates by coated samples on sapphire substrate [6]. Fig.6 shows the result of a first measurement. Bulk niobium and filtered film show the same behaviour, the slight difference being compatible with measurement uncertainties.

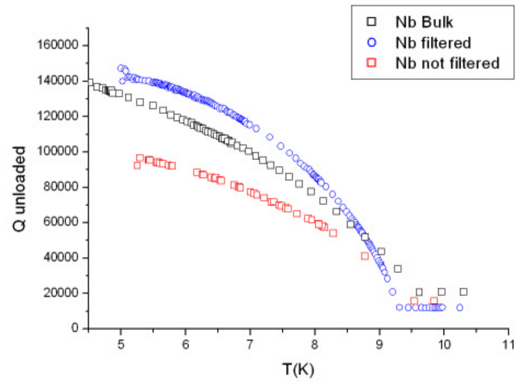

Fig. 6: Comparison between the quality factors of bulk Nb and of our film samples.

CONCLUSIONS

It has been shown that very pure, bulk-like film samples can be produced by the UHV cathodic arc deposition technique. First measurements of the deposited film RF properties at 20GHz show that they (albeit so far at low field) are also comparable to those of pure bulk Nb. Future work will address the optimisation of the deposition parameters by fully characterising samples deposited on Cu, with the end aim of upgrading the technique and the apparatus for depositing actual RF cavities. The UHV arc technique being also almost ideally suited to produce composite films with precise stechiometric composition, the deposition of higher T_c materials is also a possible development line.

REFERENCES

[1] C. Benvenuti, S. Calatroni, P. Darriulat, M.A.Peck, A.M. Valente, C.A. Van't Hof, Physica C, 351 (2001) 421-428A.

[2] D.M.Sanders, J. Vac. Sci. Technol. **A 7**, (1989) 2339.

[3] R. Russo, J.Langner, L.Catani, M.Cirillo, V.Merlo, S.Tazzari, F.Tazzioli, Proc. XII Workshop on RF Superconductivity, 6-11 Sept. 2001 Tsukuba (Japan)

[4] R. Russo et al, "UHV arc for superconducting niobium film deposition", Proc SRF 2003 Travemünde (Germany)

[5] R. Russo and S. Sgobba, Part. Acc. 60 (1999) 135-145.

[6] A. Androne et al. "Electrodynamic response of MgB2 sintered pellets and thin films", in "Studies of High Temperature Superconductors" vol. 41, A. V.Narlikar, ed., Nova Science Publ., New York, 2002.